1 DETERMINING RESISTIVITY OF A FORMATION
2 ADJACENT TO A BOREHOLE HAVING CASING
3 WITH AN APPARATUS HAVING ALL CURRENT
4 CONDUCTING ELECTRODES WITHIN THE CASED WELL
5 INS A1
6

Sub
Aa

7   This application is a Continuation-in-Part Application
8 of a Divisional Application that is entitled "Determining
9 Resistivity of a Formation Adjacent to a Borehole Having
10 Casing by Generating Constant Current Flow in Portion of
11 Casing and Using at Least Two Voltage Measurement
12 Electrodes"; which is Serial No. 08/738,924; which has the
13 filing date of 10/28/1996; and which is to issue shortly as
14 a U.S. Patent. An entire copy of Serial No. 08/738,924 is
15 included herein by reference.
16
17   Serial No. 08/738,924 is a Divisional Application of
18 a Continuation-in-Part Application that is entitled
19 "Determining Resistivity of a Formation Adjacent to a
20 Borehole Having Casing Using Multiple Electrodes and With
21 Resistances Being Defined Between the Electrodes"; which is
22 Serial No. 08/083,615; which has the filing date of 6/28/93;
23 and which issued on 10/29/96 as U.S. Patent No. 5,570,024
24 {"Vail(024)"}. An entire copy of Serial No. 08/083,615 is
25 included herein by reference.
26
27   Serial No. 08/083,615 is a Continuation-in-Part
28 Application of an earlier Divisional Application that
29 is entitled "Methods of Operation of Apparatus Measuring
30 Formation Resistivity From Within a Cased Well Having One
31 Measurement and Two Compensation Steps"; which is Serial
32 No. 07/754,965; which has the filing date of 9/4/1991; and
33 that issued on 6/29/1993 as U.S. Patent No. 5,223,794
34

{"Vail(794)"}. A entire copy of Serial No. 07/754,965 is
included herein by reference.

Serial No. 07/754,965 is a Divisional Application of an
earlier Continuation-in-Part Application that is entitled
"Electronic Measurement Apparatus Movable In a Cased Borehole
and Compensating for Casing Resistance Differences"; which is
Serial No. 07/434,886; which has the filing date of
11/13/1989; and which issued on 12/24/1991 as U.S. Patent
No. 5,075,626 {"Vail(626)"}. An entire copy of Serial
No. 07/434,886 is included herein by reference.

Serial No. 07/434,886 is a Continuation-in-Part
Application of an earlier Continuation-in-Part Application
having the title of "Methods and Apparatus for Measurement of
Electronic Properties of Geological Formations Through
Borehole Casing"; which is Serial No. 07/089,697; which has
the filing date of 08/26/1987; and which issued on 11/21/1989
as U.S. Patent No. 4,882,542 {"Vail(542)"}. An entire copy
of Serial No. 07/089,697 is included herein by reference.

Serial No. 07/089,697 is a Continuation-in-Part
Application of the original Parent Application having the
title "Methods and Apparatus for Measurement of the
Resistivity of Geological Formations from Within Cased
Boreholes"; which is Serial No. 06/927,115; which has the
filing date of 11/4/1986; and which issued on 4/11/1989
as U.S. Patent No. 4,820,989 {"Vail(989)"}. An entire copy
of Serial No. 06/927,115 is included herein by reference.

The above paragraphs define a total of 5 issued U.S.
Patents, and 1 co-pending U.S. Patent Application, that
show the "direct chain" of applications leading to the
application herein.

1   However, there are an additional 5 U.S. Patents that
2   have issued that are related to this application.   In
3   addition, there are yet 2 more U.S. Patent Applications that
4   are co-pending in the USPTO that are related to this case.
5   These are defined in the following, respectively enumerated
6   as (i), (ii), (iii), (iv), (v), (vi) and (vii).

8   (i) U.S. Patent No. 5,043,669 {"Vail(669)"} entitled
9   "Methods and Apparatus for Measurement of the Resistivity of
10   Geological Formations From Within Cased Wells in Presence of
11   Acoustic and Magnetic Energy Sources"; that issued on
12   8/27/1991; that is Serial No. 07/438,268; that has the
13   filing date of 11/16/1989; and that is a Continuation-in-Part
14   Application of Serial No. 07/089,697. An entire copy of
15   Serial No. 07/438,268 is included herein by reference.

17   (ii) U.S. Patent No. 5,043,668 {"Vail(668)"} entitled
18   "Methods and Apparatus for Measurement of Electronic
19   Properties of Geological Formations Through Borehole Casing";
20   that issued on 8/27/1991; that is Serial No. 07/435,273; that
21   has the filing date of 10/30/1989; and that is a Continuation
22   Application of Serial No. 07/089,697. An entire copy of
23   Serial No. 07/435,273 is included herein by reference.

25   (iii) U.S. Patent No. 5,187,440 {"Vail(440)"} entitled
26   "Measuring Resistivity Changes From Within a First Cased Well
27   to Monitor Fluids Injected Into Oil Bearing Geological
28   Formations From a Second Cased Well While Passing Electrical
29   Current Between the Two Cased Wells"; that issued on
30   2/16/1993; that is Serial No. 07/749,136; that has the filing
31   date of 8/23/1991; and that is a Continuation-in-Part
32   Application of Serial No. 07/435,273. An entire copy of
33   Serial No. 07/749,136 is included herein by reference.
34

1   (iv)   U.S. Patent No. 5,633,590 {"Vail(590)"} entitled
2   "Formation Resistivity Measurements from Within a Cased Well
3   Used to Quantitatively Determine the Amount of Oil and Gas
4   Present"; that issued on 5/27/1997; that is Serial
5   No. 08/214,648; that has the filing date of 3/17/1994;
6   and that is a Continuation-in-Part Application of Serial
7   No. 08/083,615. An entire copy of Serial No. 08/214,628
8   is included herein by reference.
9
10   (v)   U.S. Patent No. 5,717,334 {"Vail(334)"} entitled
11   "Methods and Apparatus to Produce Stick-Slip Motion of
12   Logging Tool Attached to a Wireline Drawn Upward by a
13   Continuously Rotating Wireline Drum"; that issued on
14   2/10/1998; that is Serial No. 08/508,781; that has the filing
15   date of 7/28/1995; that is a Continuation-in-Part Application
16   of Serial No. 08/083,615. An entire copy of Serial
17   No. 08/508,781 is included herein by reference.
18
19   (vi)   Co-pending application Serial No. 08/685,796
20   entitled "Electrical Voltages and Resistances Measured to
21   Inspect Metallic Cased Wells and Pipelines"; that has the
22   filing date of 7/23/1996; that is an FWC Application of
23   Serial No. 08/271,869 (now abandoned); and Serial
24   No. 08/271,869 is a Continuation-in-Part Application
25   of Serial No. 08/083,615. An entire copy of Serial
26   No. 08/685,796 is included herein by reference.
27
28   (vii)   Co-pending application Serial No. 08/864,309
29   entitled "Formation Resistivity Measurements from Within a
30   Cased Well Used to Quantitatively Determine the Amount of Oil
31   and Gas Present"; that has the filing date of 5/27/1997; that
32   is a Continuation Application of Serial No. 08/214,648.
33   An entire copy of Serial No. 08/864,309 is included herein
34   by reference.

The Office Action for Serial No. 08/738,924 made
by Examiner Walter E. Snow, Primary Examiner, that was mailed
on the date of 9/21/1998, had attached to it a total of seven
sheets of Form PTO-1449 specifically including: sheets 1-5
having the stamp of "OIPE OCT 26 1997"; sheet 1 having the
stamp of "OIPE JUL 25 1998"; and sheet 1 having the stamp
of "OIPE AUG 05 1996"; which seven total sheets are included
herein by their entirety by reference. Further, each and
every reference cited on those seven sheets, namely,
references AA-AV; BA-BE; CA-DO; EA-EC; and FA-FC; are
included herein in their entirety by reference. Therefore,
included herein by reference in their entirety is each and
every one of those 74 references cited in the previous
sentence.

Portions of this application have been disclosed in U.S.
Disclosure Document No. 228495, filed June 5, 1989, an entire
copy of which is included herein by reference. Other U.S.
Disclosure Documents related to this application have been
filed in the USPTO, and entire copies of all of those
U.S. Disclosure Documents are included herein by reference
(and those U.S. Disclosure Document numbers shall be provided
by applicant in a later amendment to be filed by applicant).

This invention was made with Government support under
DOE Grant No. DE-FG06-84ER13294, entitled "Validating the
Paramagnetic Logging Effect", Office of Basic Energy
Sciences, of the U.S. Department of Energy. The government
has certain rights in this invention. The basic concept for
the invention described herein was conceived during the
funding provided by the above grant.

Ongoing research to measure resistivity through
casing has been provided on a co-funded basis from:

(a) U.S. Department of Energy Grant No. DE-FG19-88BC14243
entitled "Proof of Feasibility of Thru Casing Resistivity
Technology"; (b) U.S. Department of Energy (DOE) Grant
No. DE-FG22-90BC14617 entitled "Proof of Concept of Moving
Thru Casing Resistivity Apparatus"; (c) U.S. Department of
Energy Grant No. DE-FG22-93BC14966 entitled "Fabrication and
Downhole Testing of Moving Through Casing Resistivity
Apparatus'; and (d) Gas Research Institute (GRI) Contract
No. 5088-212-1664 entitled "Proof of Feasibility of the
Through Casing Resistivity Technology". The government
and the GRI have certain rights in this invention.

This invention provides improved methods and apparatus
for measurement of the electronic properties of formations
such as the resistivities, polarization phenomena, and
dielectric constants of geological formations and cement
layers adjacent to cased boreholes and for measuring the skin
effect of the casing present. The terms "electronic
properties of formations" and "electrochemical properties of
formations" are used interchangeably herein.

The oil industry has long sought to measure resistivity
through casing. Such resistivity measurements, and
measurements of other electrochemical phenomena, are useful
for at least the following purposes: locating bypassed oil
and gas; reservoir evaluation; monitoring water floods;
measuring quantitative saturations; cement evaluation;
permeability measurements; and measurements through a drill
string attached to a drilling bit. Therefore, measurements
of resistivity and other electrochemical phenomena through
metallic pipes, and steel pipes in particular, are an
important subject in the oil industry. Many U.S. patents
have issued in the pertinent Subclass 368 of Class 324 of the
United States Patent and Trademark Office which address this

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1 subject. The following presents a brief description of the
2 particularly relevant prior art presented in the order of
3 descending relative importance.
4
5 U.S. Patents which have already issued to the inventor
6 in the is field are listed as follows:
7 U.S. Patent No. 4,820,989 (Serial No. 06/927,115);
8 U.S. Patent No. 4,882,542 (Serial No. 07/089,697);
9 U.S. Patent No. 5,043,668 (Serial No. 07/435,273);
10 U.S. Patent No. 5,043,669 (Serial No. 07/438,268);
11 U.S. Patent No. 5,075,626 (Serial No. 07/434,886);
12 U.S. Patent No. 5,187,440 (Serial No. 07/749,136);
13 U.S. Patent No. 5,223,794 (Serial No. 07/754,965);
14 U.S. Patent No. 5,570,024 (Serial No. 08/083,615);
15 U.S. Patent No. 5,633,590 (Serial No. 08/214,648); and
16 U.S. Patent No. 5,717,334 (Serial No. 08/508,781).
17
18 As of the filing date of the application herein, the
19 inventor's currently co-pending U.S. Patent Applications
20 in this field are listed as follows:
21 Serial No. 08/738,924 that is to issue shortly;
22 Serial No. 08/685,796 that is to also issue shortly; and
23 Serial No. 08/864,309 that is co-pending with the
24 application herein.
25
26 The above 10 issued U.S. Patents, and any of the
27 additional cases when they issue, are collectively identified
28 as "the Vail Patents" for the purposes herein. For the
29 record, entire copies of each and every one of the above 13
30 cases identified by serial number are included herein in
31 their entirety by reference.
32
33 The apparatus and methods of operation herein disclosed
34 are embodiments of the Through Casing Resistivity Tool® that

1   is abbreviated TCRT®. The Through Casing Resistivity Tool®
2   and TCRT® are Trademarks of ParaMagnetic Logging, Inc. in the
3   United States Patent and Trademark Office.

4

5   An important publication concerning the Through Casing
6   Resistivity Tool (TCRT) and the Vail Patents is the article
7   entitled "Formation Resistivity Measurements Through Metal
8   Casing", having authors of W.B. Vail and S.T. Momii of
9   ParaMagnetic Logging, Inc., R. Woodhouse of Petroleum and
10 Earth Science Consulting, M. Alberty and R.C.A. Peveraro of
11 BP Exploration, and J.D. Klein of Arco Exploration and
12 Production Technology, which appeared as Paper "F", Volume I,
13 in the Transactions of the SPWLA Thirty-Fourth Annual Logging
14 Symposium, Calgary, Alberta, Canada, June 13-16, 1993,
15 sponsored by The Society of Professional Well Log Analysts,
16 Inc. of Houston, Texas and the Canadian Well Logging Society
17 of Calgary, Alberta, Canada (13 pages of text and
18 8 additional figures); an entire copy of which is included
19 herein by reference. Experimental results are presented
20 therein which confirm that the apparatus and methods
21 disclosed the Vail Patents actually work in practice to
22 measure the resistivity of geological formations adjacent to
23 cased wells. To the author's knowledge, this SPWLA paper
24 presents the first accurate measurements of resistivity
25 obtained from within cased wells using any previous
26 experimental apparatus.

27

28   Another important publication related to the Vail
29 Patents is the article entitled "Formation Resistivity
30 Measurements Through Metal Casing at the MWX-2 Well in Rifle,
31 Colorado", having the authors of W.B. Vail and S.T. Momii of
32 ParaMagnetic Logging, Inc., H. Haines of Gas Research
33 Institute, J.F. Gould, Jr. of Mobil Exploration & Producing
34 U.S., and W.D. Kennedy of the Mobil Research and Development

Corporation, which appeared as Paper "OO" in the SPWLA 36th
Annual Logging Symposium, Paris, France, June 26-29, 1995,
Sponsored by The Society of Professional Well Log Analysts,
Inc., 12 pages including Figures 1-5, an entire copy of which
is included herein by reference.

Yet another important publication related to the Vail
Patents is the article entitled "Through Casing Resistivity
Measurements and Their Interpretation for Hydrocarbon
Saturations", having the authors of W.B. Vail and S.T. Momii
of ParaMagnetic Logging, Inc., and J.T. Dewan of Dewan &
Timko, Inc., that is SPE Paper 30582, presented at the SPE
Annual Technical Conference & Exhibition, Dallas, Texas,
October 22-26, 1995, pages 533-548, including Figures 1-18,
an entire copy of which is included herein by reference.

Yet another important publication related to the Vail
Patents is the article entitled "Through Casing Resistivity
Tool™ To Locate Bypassed Oil", having the authors of
W. Banning Vail, Steven T. Momii, and Richard Woodhouse, that
appeared in The American Oil & Gas Reporter, October, 1995,
pages 70-76, including Figures 1-3, an entire copy of which
is included herein by reference.

And yet another extensive publication related to the
Vail Patents is the document entitled "Proof of Feasibility
of the Through Casing Resistivity Technology", that is the
Final Report to Gas Research Institute for research work
performed from the dates of April 1988 to March 1994 under
GRI Contract No. 5088-212-1664, having the authors of
W.B. Vail and S.T. Momii of ParaMagnetic Logging,
March, 1996, having a total of 328 pages and 169 figures, an
entire copy of which is included herein by reference. This
Final Report dated March, 1996 is a revised version of an

earlier document entitled "First Draft of the Final Report to GRI" and dated July 4, 1994, an entire copy of which is also incorporated herein by reference.

The Vail Patents describe the various embodiments of the Through Casing Resistivity Tool® (TCRT®). Many of these Vail Patents describe embodiments of apparatus having three or more spaced apart voltage measurement electrodes which engage the interior of the casing, and which also have calibration means to calibrate for thickness variations of the casing and for errors in the placements of the voltage measurement electrodes.

U.S. Patent No. 4,796,186 which issued on January 3, 1989 to Alexander A. Kaufman entitled "Conductivity Determination in a Formation Having a Cased Well" also describes apparatus having three or more spaced apart voltage measurement electrodes which engage the interior of the casing and which also have calibration means to calibrate for thickness variations in the casing and for errors in the placements of the electrodes. This patent has been assigned to ParaMagnetic Logging, Inc. of Woodinville, Washington. In general, different methods of operation and analysis are described in the Kaufman Patent compared to the Vail Patents cited above.

U.S. Patent No. 4,837,518 which issued on June 6, 1989 to Michael F. Gard, John E. E. Kingman, and James D. Klein, assigned to the Atlantic Richfield Company, entitled "Method and Apparatus for Measuring the Electrical Resistivity of Geologic Formations Through Metal Drill Pipe or Casing", predominantly describes two voltage measurement electrodes and several other current introducing electrodes disposed vertically within a cased well which electrically

engage the wall of the casing, henceforth referenced as "the Arco Patent". However, the Arco Patent does not describe an apparatus having three spaced apart voltage measurement electrodes and associated electronics which takes the voltage differential between two pairs of the three spaced apart voltage measurement electrodes to directly measure electronic properties adjacent to formations. Nor does the Arco Patent describe an apparatus having at least three spaced apart voltage measurement electrodes wherein the voltage drops across adjacent pairs of the spaced apart voltage measurement electrodes are simultaneously measured to directly measure electronic properties adjacent to formations. Therefore, the Arco Patent does not describe the methods and apparatus disclosed herein.

USSR Patent No. 56,026, which issued on November 30, 1939 to L. M. Alpin, henceforth called the "Alpin Patent", which is entitled "Process of the Electrical Measurement of Well Casings", describes an apparatus which has three spaced apart voltage measurement electrodes which positively engage the interior of the casing. However, the Alpin Patent does not have any suitable calibration means to calibrate for thickness variations of the casing nor for errors related to the placements of the voltage measurement electrodes. Therefore, the Alpin Patent does not describe the methods and apparatus disclosed herein.

French Patent No. 2,207,278 having a "Date of Deposit" of November 20, 1972 (hereinafter "the French Patent") describes apparatus having four spaced apart voltage measurement electrodes which engage the interior of borehole casing respectively defined as electrodes M, N, K, and L. Various uphole and downhole current introducing electrodes are described. Apparatus and methods of operation are

1 provided that determines the average resistance between
2 electrodes M and L. This French Patent further explicitly
3 assumes an exponential current flow along the casing.
4 Voltage measurements across pair MN and KL are then used to
5 infer certain geological parameters from the assumed
6 exponential current flow along the casing. ...However, the
7 French Patent does not teach measuring a first casing
8 resistance between electrodes MN, does not teach measuring a
9 second casing resistance between electrodes NK, and does not
10 teach measuring a third casing resistance between electrodes
11 KL. The invention herein and other preferred embodiments
12 described in the Vail Patents teach that it is of importance
13 to measure said first, second, and third resistances to
14 compensate current leakage measurements for casing thickness
15 variations and for errors in placements of the voltage
16 measurement electrodes along the casing to provide accurate
17 measurements of current leakage into formation. Further,
18 many embodiments of the Vail Patents do not require any
19 assumption of the form of current flow along the casing to
20 measure current leakage into formation. Therefore, for these
21 reasons alone, the French Patent does not describe the
22 methods and apparatus disclosed herein. There are many other
23 differences between various embodiments of the Vail Patents
24 and the French Patent which are described in great detail in
25 the Statement of Prior Art for Serial No. 07/754,965 dated
26 December 2, 1991 that issued as U.S. Patent No. 5,223,794
27 on June 29, 1993.

28

29   An abstract of an article entitled "Effectiveness of
30 Resistivity Logging of Cased Wells by A Six-Electrode Tool"
31 by N.V. Mamedov was referenced in TULSA ABSTRACTS as follows:
32 "IZV.VYSSH.UCHEB, ZAVEDENII, NEFT GAZ no.7, pp. 11-15, July
33 1987. (ISSN 0445-0108; 5 refs; in Russian)", hereinafter the
34 "Russian Article". It is the applicant's understanding from

an English translation of that Russian Article that the article itself mathematically predicts the sensitivity of the type tool described in the above defined French Patent. The Russian Article states that the tool described in the French Patent will only be show a "weak dependence" on the resistivity of rock adjacent to the cased well. By contrast, many embodiments of the Vail Patents, and the invention herein, provide measurements of leakage current and other parameters which are strongly dependent upon the resistivity of the rock adjacent to the cased well. Therefore, this Russian Article does not describe the methods and apparatus disclosed herein.

U.S. Patent No. 2,729,784, issued on January 3, 1956 having the title of "Method and Apparatus for Electric Well Logging", and U.S. Patent No. 2,891,215 issued on June 16, 1959 having the title of "Method and Apparatus for Electric Well Logging", both of which issued in the name of Robert E. Fearon, henceforth called the "Fearon Patents", describe apparatus also having two pairs of voltage measurement electrodes which engage the interior of the casing. However, an attempt is made in the Fearon Patents to produce a "virtual electrode" on the casing in an attempt to measure leakage current into formation which provides for methods and apparatus which are unrelated to the Kaufman and Vail Patents cited above. The Fearon Patents neither provide calibration means, nor do they provide methods similar to those described in either the Kaufman Patent or the Vail Patents, to calibrate for thickness variations and errors in the placements of the electrodes. Therefore, the Fearon Patents do not describe the methods and apparatus disclosed herein.

Accordingly, an object of the invention is to provide new and practical apparatus having three or more spaced apart

1 voltage measurement electrodes to measure formation
2 resistivity from within cased wells.
3
4 It is yet another object of the invention is to provide
5 new methods of operation of the multi-electrode apparatus to
6 measure formation from within cased wells which compensates
7 for casing resistance differences and which compensates for
8 errors in placements of the voltage measurement electrodes.
9
10 And it is yet another object of the invention to provide
11 an apparatus, and suitable methods of operation, to determine
12 the resistivity of a formation adjacent to a borehole having
13 casing with an apparatus having all current conducting
14 electrodes located within the cased well.
15
16 Figure 1 is a sectional view of one preferred embodiment
17 of the invention of the Through Casing Resistivity Tool
18 (TCRT) which is marked with the legend "Prior Art".
19
20 Figure 2 shows ΔI vs. Z which diagrammatically depicts
21 the response of the tool to different formations which is
22 marked with the legend "Prior Art".
23
24 Figure 3 is a sectional view of a preferred embodiment
25 of the invention which shows how V_o is to be measured that is
26 marked with the legend "Prior Art".
27
28 Figure 4 is a sectional view of an embodiment of the
29 invention which has voltage measurement electrodes which are
30 separated by different distances that is marked with the
31 legend "Prior Art".
32
33 Figure 5 is a sectional view of an embodiment of the
34 invention which has electrodes which are separated by

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1 different distances and which shows explicitly how to measure
2 V_O that is marked with the legend "Prior Art".
3
4 Figure 6 is a sectional view of an embodiment of the
5 invention which provides multi-frequency operation to
6 compensate for errors of measurement marked with the legend
7 "Prior Art".
8
9 Figure 7 is a sectional view of an embodiment of the
10 invention that eliminates the use of a certain differential
11 amplifier.
12
13 Figure 8 is a sectional view of an embodiment of the
14 invention that possesses four spaced apart voltage
15 measurement electrodes.
16
17 Figure 9 is a sectional view of an embodiment of the
18 invention that possesses four spaced apart voltage
19 measurement electrodes and extra current introducing
20 electrodes.
21
22 Figure 10 is a multi-electrode apparatus designed to
23 keep certain currents flowing along the casing constant in
24 amplitude in the vicinity of four spaced apart voltage
25 measurement electrodes used to measure resistivity.
26
27 Figure 11 is a multi-electrode apparatus designed to
28 keep certain currents flowing along the casing constant in
29 amplitude in the vicinity of three spaced apart voltage
30 measurement electrodes used to measure resistivity.
31
32 Figure 12 is an apparatus having three spaced apart
33 voltage measurement electrodes and extra current introducing
34 electrodes.

1   Figure 13 is functionally identical to Figure 26 from
2   Serial No. 07/089,697 that is U.S. Patent No. 4,882,542,
3   showing an apparatus having multiple voltage measurement
4   electrodes engaging the interior of the casing that is marked
5   with the legend "Prior Art".
6
7   Figure 14 is identical to Figure 24 from Serial
8   No. 07/089,697 that is U.S. Patent No. 4,882,542 that shows
9   an apparatus for determining the resistivity of a formation
10 adjacent to a borehole having casing wherein all current
11 conducting electrodes are located within the cased well
12 when element 22 is connected through SW1C to electrode B_1.
13 It is marked with the legend "Prior Art".
14
15   The invention is described in three major different
16 portions of the specification. In the first major portion of
17 the specification, relevant parts of the text in Serial
18 No. 07/089,697 {Vail(542)} are repeated herein which describe
19 apparatus defined in Figures 1, 3, 4, and 5. The second
20 major portion of the specification quotes relevant parts of
21 Serial No. 07/434,886 {Vail(626)} that describe the apparatus
22 defined in Figure 6. The third major portion of the
23 specification herein is concerned with providing multi-
24 electrode apparatus and methods of operation of the multi-
25 electrode apparatus to measure formation resistivity from
26 within cased wells that compensates for casing resistance
27 differences and for errors in placements of the various
28 voltage measurement electrodes. The definitions provided in
29 Figures 1 through 6 are used to conveniently define many of
30 the symbols appearing in Figures 7 through 12.
31
32   From a technical drafting point of view, Figures 1, 2,
33 3, 4, and 5 in Serial No. 07/089,697 {Vail(542)} and in those
34 contained in this application are nearly identical. However,

1   the new drawings have been re-done using computer graphics
2   and the A-4 International Size. The following excerpt is
3   taken word-for-word from Serial No. 07/089,697:
4
5   "Fig. 1 shows a typical cased borehole found in an oil
6   field. The borehole 2 is surrounded with borehole casing 4
7   which in turn is held in place by cement 6 in the rock
8   formation 8. An oil bearing strata 10 exists adjacent to the
9   cased borehole. The borehole casing may or may not extend
10   electrically to the surface of the earth 12. A voltage
11   signal generator 14 (SG) provides an A.C. voltage via cable
12   16 to power amplifier 18 (PA). The signal generator
13   represents a generic voltage source which includes relatively
14   simple devices such as an oscillator to relatively complex
15   electronics such as an arbitrary waveform generator. The
16   power amplifier 18 is used to conduct A.C. current down
17   insulated electrical wire 20 to electrode A which is in
18   electrical contact with the casing. The current can return
19   to the power amplifier through cable 22 using two different
20   paths. If switch SW1 is connected to electrode B which is
21   electrically grounded to the surface of the earth, then
22   current is conducted primarily from the power amplifier
23   through cable 20 to electrode A and then through the casing
24   and cement layer and subsequently through the rock formation
25   back to electrode B and ultimately through cable 22 back
26   to the power amplifier. In this case, most of the current is
27   passed through the earth. Alternatively, if SW1 is connected
28   to insulated cable 24 which in turn is connected to electrode
29   F, which is in electrical contact with the casing, then
30   current is passed primarily from electrode A to electrode F
31   along the casing for a subsequent return to the power
32   amplifier through cable 22. In this case, little current
33   passes through the earth.
34

Electrodes C, D, and E are in electrical contact with
the interior of casing. In general, the current flowing
along the casing varies with position. For example, current
I_C is flowing downward along the casing at electrode C,
current I_D is flowing downward at electrode D, and current I_E
is flowing downward at electrode E. In general, therefore,
there is a voltage drop V1 between electrodes C and D which
is amplified differentially with amplifier 26. And the
voltage difference between electrodes D and E, V2, is also
amplified with amplifier 28. With switches SW2 and SW3 in
their closed position as shown, the outputs of amplifiers 26
and 28 respectively are differentially subtracted with
amplifier 30. The voltage from amplifier 30 is sent to the
surface via cable 32 to a phase sensitive detector 34. The
phase sensitive detector obtains its reference signal from
the signal generator via cable 36. In addition, digital gain
controller 38 (GC) digitally controls the gain of amplifier
28 using cable 40 to send commands downhole. The gain
controller 38 also has the capability to switch the input
leads to amplifier 28 on command, thereby effectively
reversing the output polarity of the signal emerging from
amplifier 28 for certain types of measurements.

The total current conducted to electrode A is measured
by element 42. In the preferred embodiment shown in Fig. 1,
the A.C. current used is a symmetric sine wave and therefore
in the preferred embodiment, I is the 0-peak value of the
A.C. current conducted to electrode A. (The 0-peak value of
a sine wave is 1/2 the peak-to-peak value of the sine wave.)

In general, with SW1 connected to electrode B, current
is conducted through formation. For example, current ΔI is
conducted into formation along the length 2L between
electrodes C and E. However, if SW1 is connected to cable 24

1   and subsequently to electrode F, then no current is conducted
2   through formation to electrode B. In this case, $I_C = I_D = I_E$
3   since essentially little current ΔI is conducted into
4   formation.

5

6   It should be noted that if SW1 is connected to electrode
7   B then the current will tend to flow through the formation
8   and not along the borehole casing. Calculations show that
9   for 7 inch O.D. casing with a 1/2 inch wall thickness that if
10   the formation resistivity is 1 ohm-meter and the formation is
11   uniform, then approximately half of the current will have
12   flowed off the casing and into the formation along a length
13   of 320 meters of the casing. For a uniform formation with a
14   resistivity of 10 ohm-meters, this length is 1040 meters
15   instead." These lengths are respectively called
16   "Characteristic Lengths" appropriate for the average
17   resistivity of the formation and the type of casing used. A
18   Characteristic Length is related to the specific length of
19   casing necessary for conducting on approximately one-half the
20   initial current into a particular geological formation as
21   described below.

22

23   One embodiment of the invention described in Serial
24   No. 07/089,697 {Vail(542)} provides a preferred method of
25   operation for the above apparatus as follows: "The first
26   step in measuring the resistivity of the formation is to
27   "balance" the tool. SW1 is switched to connect to cable 24
28   and subsequently to electrode F. Then A.C. current is passed
29   from electrode A to electrode F thru the borehole casing.
30   Even though little current is conducted into formation, the
31   voltages V1 and V2 are in general different because of
32   thickness variations of the casing, inaccurate placements of
33   the electrodes, and numerous other factors. However, the
34   gain of amplifier 28 is adjusted using the gain controller so

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that the differential voltage V3 is nulled to zero.
(Amplifier 28 may also have phase balancing electronics if
necessary to achieve null at any given frequency of
operation.) Therefore, if the electrodes are subsequently
left in the same place after balancing for null, spurious
effects such as thickness variations in the casing do not
affect the subsequent measurements.

   With SW1 then connected to electrode B, the signal
generator drives the power amplifier which conducts current
to electrode A which is in electrical contact with the
interior of the borehole casing. A.C. currents from
1 amp o-peak to 30 amps o-peak at a frequency of typically 1
Hz are introduced on the casing here. The low frequency
operation is limited by electrochemical effects such as
polarization phenomena and the invention can probably be
operated down to .1 Hz and the resistivity still properly
measured. The high frequency operation is limited by skin
depth effects of the casing, and an upper frequency limit of
the invention is probably 20 Hz for resistivity measurements.
Current is subsequently conducted along the casing, both up
and down the casing from electrode A, and some current passes
through the brine saturated cement surrounding the casing and
ultimately through the various resistive zones surrounding
the casing. The current is then subsequently returned to the
earth's surface through electrode B."

   Quoting further from Serial No. 07/089,697 {Vail(542)}:
"Fig. 2 shows the differential current conducted into
formation ∆I for different vertical positions z within a
steel cased borehole. Z is defined as the position of
electrode D in Fig. 1. It should be noted that with a
voltage applied to electrode A and with SW1 connected to
electrode B that this situation consequently results in a

radially symmetric electric field being applied to the
formation which is approximately perpendicular to the casing.
The electrical field produces outward flowing currents such
as ΔI in Fig. 1 which are inversely proportional to the
resistivity of the formation. Therefore, one may expect
discontinuous changes in the current ΔI at the interface
between various resistive zones particularly at oil/water and
oil/gas boundaries. For example, curve (a) in Fig. 2 shows
the results from a uniform formation with resistivity ρ_1.
Curve (b) shows departures from curve (a) when a formation of
resistivity ρ_2 and thickness T_2 is intersected where ρ_2 is
less than ρ_1. And curve (c) shows the opposite situation
where a formation is intersected with resistivity ρ_3 which is
greater than ρ_1 which has a thickness of T_3. It is obvious
that under these circumstances, ΔI_3 is less than ΔI_1, which
is less than ΔI_2.

Fig. 3 shows a detailed method to measure the parameter
Vo. Electrodes A, B, C, D, E, and F have been defined in
Fig. 1. All of the numbered elements 2 through 40 have
already been defined in Fig. 1. In Fig. 3, the thickness of
the casing is τ_1, the thickness of the cement is τ_2, and d is
the diameter of the casing. Switches SW1, SW2, and SW3 have
also been defined in Fig. 1. In addition, electrode G is
introduced in Fig. 3 which is the voltage measuring reference
electrode which is in electrical contact with the surface of
the earth. This electrode is used as a reference electrode
and conducts little current to avoid measurement errors
associated with current flow.

In addition, SW4 is introduced in Fig. 3 which allows
the connection of cable 24 to one of the three positions:
to an open circuit; to electrode G; or to the top of the
borehole casing. And in addition in Fig. 3, switches SW5,

1   SW6, and SW7 have been added which can be operated in the
2   positions shown.   (The apparatus in Fig. 3 can be operated in
3   an identical manner as that shown in Fig. 1 provided that
4   switches SW2, SW5, SW6, and SW7 are switched into the
5   opposite states as shown in Fig. 3 and provided that SW4
6   is placed in the open circuit position.)
7
8   With switches SW2, SW5, SW6, and SW7 operated as shown
9   in Fig. 3, then the quantity Vo may be measured.   For a given
10 current I conducted to electrode A, then the casing at that
11 point is elevated in potential with respect to the zero
12 potential at a hypothetical point which is an "infinite"
13 distance from the casing.   Over the interval of the casing
14 between electrodes C, D, and E in Fig. 3, there exists an
15 average potential over that interval with respect to an
16 infinitely distant reference point.   However, the potential
17 measured between only electrode E and electrode G
18 approximates Vo provided the separation of electrodes A, C,
19 D, and E are less than some critical distance such as 10
20 meters and provided that electrode G is at a distance
21 exceeding another critical distance from the casing such as
22 10 meters from the borehole casing.   The output of amplifier
23 28 is determined by the voltage difference between electrode
24 E and the other input to the amplifier which is provided by
25 cable 24.   With SW1 connected to electrode B, and SW4
26 connected to electrode G, cable 24 is essentially at the same
27 potential as electrode G and Vo is measured appropriately
28 with the phase sensitive detector 34.   In many cases, SW4 may
29 instead be connected to the top of the casing which will work
30 provided electrode A is beyond a critical depth ...".
31
32   Quoting further from Serial No. 07/089,697 {Vail(542)}:
33 "For the purposes of precise written descriptions of the
34 invention, electrode A is the upper current conducting

electrode which is in electrical contact with the interior of
the borehole casing; electrode B is the current conducting
electrode which is in electrical contact with the surface of
the earth; electrodes C, D, and E are voltage measuring
electrodes which are in electrical contact with the interior
of the borehole casing; electrode F is the lower current
conducting electrode which is in electrical contact with the
interior of the borehole casing; and electrode G is the
voltage measuring reference electrode which is in electrical
contact with the surface of the earth.

Furthermore, V_O is called the local casing potential.
An example of an electronics difference means is the
combination of amplifiers 26, 28, and 30. The differential
current conducted into the formation to be measured is ΔI."
The differential voltage is that voltage in Figure 1 which is
the output of amplifier 30 with SW1 connected to electrode B
and with all the other switches in the positions shown.

Further quoting from Serial No. 07/089,697 {Vail(542)}:
"Fig. 4 is nearly identical to Fig. 1 except the electrodes C
and D are separated by length L_1, electrodes D and E are
separated by L_2, electrodes A and C are separated by L_3 and
electrodes E and F are separated by the distance L_4. In
addition, r_1 is the radial distance of separation of
electrode B from the casing. And Z is the depth from the
surface of the earth to electrode D. Fig. 5 is nearly
identical to Fig. 3 except here too the distances L_1, L_2, L_3,
L_4, r_1, and Z are explicitly shown. In addition, r_2 is also
defined which is the radial distance from the casing to
electrode G. As will be shown explicitly in later analysis,
the invention will work well if L_1 and L_2 are not equal. And
for many types of measurements, the distances L_3 and L_4 are

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1   not very important provided that they are not much larger in
2   magnitude than L_1 and L_2."

3

4   Figure 6 was first described in Serial No. 07/434,886
5   {Vail(626)} which states: "For the purpose of logical
6   introduction, the elements in FIG. 6 are first briefly
7   compared to those in FIGS. 1-5.   Elements No. 2, 4, 6, 8,
8   and 10 have already been defined. Electrodes A, B, C, D, E,
9   F, G and the distances L_1, L_2, L_3, and L_4 have already been
10   described. The quantities δi_1 and δi_2 have already been
11   defined in the above text. Amplifiers labeled with legends
12   A1, A2, and A3 are analogous respectively to amplifiers 26,
13   28, and 30 defined in FIGS. 1, 3, 4, and 5. In addition, the
14   apparatus in Fig. 6 provides for the following:
15   (a) two signal generators labeled with legends "SG 1 at
16   Freq F(1)" and "SG 2 at Freq F(2)";
17   (b) two power amplifiers labeled with legends "PA 1"
18   and "PA 2";
19   (c) a total of 5 phase sensitive detectors defined as
20   "PSD 1", "PSD 2", "PSD 3", "PSD 4", and "PSD 5", which
21   respectively have inputs for measurement labeled as "SIG",
22   which have inputs for reference signals labeled as "REF",
23   which have outputs defined by lines having arrows pointing
24   away from the respective units, and which are capable of
25   rejecting all signal voltages at frequencies which are not
26   equal to that provided by the respective reference signals;
27   (d) an "Error Difference Amp" so labeled with this
28   legend in FIG. 6;
29   (e) an instrument which controls gain with voltage,
30   typically called a "voltage controlled gain", which is
31   labeled with legend "VCG";
32   (f) an additional current conducting electrode labeled
33   with legend "H" (which is a distance L_5 - not shown - above
34   electrode A);

1   (g) an additional voltage measuring electrode labeled
2   with legend J (which is a distance L_6 - not shown - below
3   electrode F);
4   (h) current measurement devices, or meters, labeled
5   with legends "I1" and "I2";
6   (i) and differential voltage amplifier labeled with
7   legend "A4" in Fig. 6."
8
9   Serial No. 07/434,886 {Vail(626)} further describes
10   various cables labeled with legends respectively 44, 46, 48,
11   50, 52, 54, 56, 58, 60, 62, and 64 whose functions are
12   evident from Figure 6.
13
14   Serial No. 07/434,886 {Vail)626)} further states: "The
15   outputs of PSD 1, 2, 3, and 4 are recorded on a digital
16   recording system 70 labeled with legend "DIG REC SYS". The
17   respective outputs of the phase sensitive detectors are
18   connected to the respective inputs of the digital recording
19   system in FIG. 6 according to the legends labeled with
20   numbers 72, 74, 76, 78, and 80. One such connection is
21   expressly shown in the case of element no. 72."
22
23   Serial No. 07/434,886 {Vail(626)} teaches in great
24   detail that it is necessary to accurately measure directly,
25   or indirectly, the resistance between electrodes C-D (herein
26   defined as "R1") and the resistance between electrodes D-E
27   (herein defined as "R2") in Figures 1, 3, 4, 5 and 6 to
28   precisely measure current leakage into formation and
29   formation resistivity from within the cased well. Please
30   refer to Equations 1-33 in Serial No. 07/434,886 {Vail(626)}
31   for a thorough explanation of this fact. The parent
32   application, Serial No. 06/927,115 {Vail(989)} and
33   the following Continuation-in-Part Application Serial
34   No. 07/089,697 {Vail(542)} taught that measurement of the

1   resistance of the casing between voltage measurement
2   electrodes that engage the interior of the casing are very
3   important to measure formation resistivity from within the
4   casing.
5
6   Using various different experimental techniques that
7   result in current flow along the casing between current
8   conducting electrodes A and F in Figures 1, 3, 4, 5, and 6
9   result in obtaining first compensation information related to
10   a first casing resistance defined between voltage measurement
11   electrodes C and D. Similarly, using various different
12   experimental techniques that result in current flow along the
13   casing between current conducting electrodes A and F in
14   Figures 1, 3, 4, 5, and 6 result in obtaining second
15   compensation information related to a second casing
16   resistance between voltage measurement electrodes D and E.
17   Figures 1, 3, 4, 5, and 6 all provide additional means to
18   cause current to flow into formation, and the measurements
19   performed while current is flowing into the formation is
20   called the measurement information related to current flow
21   into formation. Such measurement information is used to
22   determine a magnitude relating to formation resistivity.
23   Figures 7 -12 in the remaining application also provide
24   various means to provide measurement information, and
25   respectively first and second compensation information, along
26   with additional information in several cases.
27
28   Figure 7 is closely related to Figure 6. However, in
29   Figure 7, amplifier A3 that is shown in Figure 6, which can
30   be either downhole, or uphole, has been removed. Further,
31   the Error Difference Amp, cable 60, and the VCG have also
32   been removed. In Figure 7, the output of amplifier A1 at
33   frequency F(1) is measured by PSD 4 and the output of
34   amplifier A1 at frequency F(2) is measured by PSD 2 - as was

the case in Figure 6. However, in Figure 7, the output of
amplifier A2 at F(1) is measured by PSD 1 and the output of
amplifier A2 at F(2) is measured by PSD 3. In Figure 7,
current at the frequency of F(1) is conducted into formation
resulting in measurement information being obtained from PSD
1 and PSD 4. Current at the frequency of F(2) is caused to
flow along the casing between electrodes H and F to provide
compensation for casing thickness variations and to provide
compensation for errors in the placement of the voltage
measurement electrodes. First compensation information
related to the casing resistance between electrodes C and D
is obtained from PSD 2. Second compensation information
related to the casing resistance between electrodes D and E
is obtained from PSD 3. Analogous algebra exists for the
operation of the apparatus in Figure 7 to Equations 1-33 in
Serial No. 07/434,886 {Vail(626)} that provides compensation
for casing resistance differences and for errors of
placements of the three spaced apart voltage measurement
electrodes C, D, and E.

Figure 8 is similar to Figure 7 except that electrode D
in Figure 7 has been intentionally divided into two separate
electrodes D1 and D2. D1 and D2 do not overlap and are
separated by a distance L9. Electrodes C and D1 are
separated by distance L1*. Electrodes D2 and E are separated
by the distance L2*. If D(1) and D(2) overlap, then the
invention has the usual configuration described in Figures 1,
3, 4, 5, 6, and 7. Then consider the situation wherein
electrodes D(1) and D(2) do not overlap. Suppose they are
separated by 1 inch. Then suppose that the separation
distance between C to D(1) is 20 inches and suppose that the
separation distance between D(2) to E is also 20 inches.
Then clearly, the invention will still work, although there
will be some error in the current leakage measurement caused

1 by the lack of measurement information from the 1 inch
2 segment. Perhaps the error shall be on the order of 1 inch
3 divided by 20 inches, or on the order of an approximate 5%
4 error. Figure 8 shows an apparatus having four spaced apart
5 voltage measurement electrodes that compensates for casing
6 thickness variations and for errors in placements of
7 electrodes by providing measurements of the casing resistance
8 R1 between electrodes C and D1 at the frequency of F(2)
9 by PSD 2 and by providing measurements of the casing
10 resistance R2 between electrodes D2 and E at the frequency
11 F(2) by PSD 3.

13   Figure 8 may be operated in a particularly simple
14 manner. The signal between electrodes C - D1 can be used to
15 control current flowing along the casing at the frequency
16 F(1) (by using electronics, not shown, of the type used to
17 control currents in Figure 6). Then the signal between
18 electrodes D2 - E can be used to measure information related
19 to current flow along the casing and into the formation at
20 the frequency of F(1). Despite the fact that electrodes C-
21 D1 are used to "control current", nonetheless, the apparatus
22 so described requires at least 3 spaced apart voltage
23 measurement electrodes and is therefore another embodiment of
24 the invention herein.

26   Figure 9 shows certain changes to the apparatus defined
27 in Figure 8. Changes from Figure 8 includes cables 88 and 90
28 that are meant to convey signals to the appropriate phase
29 sensitive detectors shown in Figure 8 for the purposes of
30 simplicity; extra variable resistor labeled with legend "VR1"
31 placed in series with current meter labeled with legend "I1"
32 connected to cable 92 that provides current at the frequency
33 of F(1) to the upper current conducting electrode here
34 defined as A1; extra variable resistor labeled with legend

"VR2" placed in series with another current meter labeled with legend "I3" connected to cable 94 that provides current at the frequency of F(1) to new electrode A2. Electrodes H and F are shown connected to cables 98 and 100 respectively which operate as shown in Figure 8, but many of the details are omitted in Figure 9 in the interest of simplicity. In Figure 9, current at the frequency of F(2) is passed between electrodes H and F as in Figure 8 which provides first compensation information related to current flow through the casing resistance ("R1") between electrodes C-D1 and second compensation information related to current flow through the casing resistance ("R2") between electrodes D2-E, although many of the details are not shown in Figure 9 for the purposes of simplicity. The purpose of electrodes A1 and A2 in Figure 9 are to provide simultaneously upward and downward flowing currents along the casing at the frequency of F(1). Such simultaneously upward and downward flowing currents along the casing are hereinafter defined as "counter-flowing currents". Such counter-flowing currents in the vicinity of the voltage measurement electrodes C, D1, D2, and E minimize the "common mode signal" input to the amplifiers A1 and A2. Therefore, the signal output of amplifiers A1 and A2 in the presence of such counter-flowing currents tends to be more responsive to the current actually flowing into formation and less responsive to the relatively larger currents flowing along the casing. Other apparatus showing methods of introducing counter-flowing currents on the casing include Figures 22 and 23 of Serial No. 07/089,697 {Vail(542)}. The current actually flowing into the formation at the frequency of F(1) generates voltages across amplifiers A1 and A2 responsive to the current flow into formation that results in measurement information at the frequency of F(1) from phase sensitive detectors as shown in Figure 8. That measurement information is used to determine a magnitude relating to

1 formation resistivity, including information related to the
2 resistivity of the adjacent geological formation.
3
4 Figure 10 improves the measurement accuracy of the
5 apparatus defined in Figure 9. Figure 10 is similar to
6 Figure 9 except that in Figure 10 extra voltage measurements
7 P, Q, R, and S have been added. The purpose of additional
8 voltage measurement electrodes P and Q are to sense the
9 current flowing along the casing at the frequency of F(1)
10 between P and Q. Further electronics, not shown, are used to
11 control the variable resistor VR1 such that the current
12 flowing along the casing remains relatively constant at the
13 frequency of F(1). Please recall that electrodes H and F are
14 used to conduct current along the casing at the frequency of
15 F(2) and therefore, measurements of the potential difference
16 between P and Q can be used to measure the casing resistance
17 between P and Q that is called "R3" which is therefore used
18 as necessary information to keep the current flowing at the
19 frequency F(1) through R3. Figure 6 has already provided
20 means to maintain equality of currents flowing along the
21 casing, and similar apparatus can be adapted herein to
22 maintain the equality of current flow at the frequency of
23 F(1) between P and Q. Similarly comments can be made
24 regarding new electrodes R and S which can be used to keep
25 the current flowing along the casing at the frequency of F(1)
26 constant through the casing resistance between electrodes R
27 and S, that is "R4" by controlling the variable resistor VR2.
28 If the current flowing through R3 at F(1) is held constant as
29 the device vertically logs the well, then that shall serve to
30 minimize the influence of the lack of information caused by
31 the separation of electrodes D1 and D2. Similarly, if the
32 current flowing through R4 at F(1) is held constant, that too
33 serves to minimize the influence of the lack of information
34 caused by the separation between electrodes D1 and D2.

1   Consequently, extra current control means have been provided
2   to control the current flow along the casing at the F(1) to
3   minimize the influence of the lack of information from
4   portions of the casing having no voltage measurement
5   electrodes present. With suitably added amplifiers, these
6   new electrode pairs can be used to independently monitor the
7   counter-flowing currents at the measurement frequency at the
8   positions shown. In particular, electrode pairs P-Q and R-S
9   can be provided with amplifiers and feedback circuitry that
10   drives the currents to A1 and A2 such that the counter-
11   flowing current at the measurement frequency (for example, 1
12   Hz) is driven near zero across the voltage measurement
13   electrodes C-D1 and D2-E. Regardless of the details of
14   operation chosen however, the invention disclosed in Figure
15   10 provides four spaced electrodes means that provides
16   measurement information related to current flow into
17   formation, and respectively, first and second compensation
18   information related to measurements of R1 and R2 between
19   respectively electrodes C-D, and D-E that are used to
20   determine a magnitude related to formation resistivity.
21   Altogether, Figure 10 shows a total of 8 each voltage
22   measurement electrodes operated as 4 pairs of voltage
23   measurement electrodes.
24
25   Figure 11 is similar to Figure 10 except that electrodes
26   D1 and D2 have been re-combined back into one single
27   electrode D herein. However, the extra potential voltage
28   measurement electrodes P-Q, and R-S remain in Figure 11 to
29   maintain equality of the magnitude of the counter-flowing
30   currents along the casing at the frequency of F(1).
31   Maintaining the equality of counter-flowing currents along
32   the casing at F(1), and ideally causing the counter-flowing
33   currents to approach the limit of zero net current flowing up
34   or down the casing at the frequency of F(1) will result in

1 improved measurement accuracy.   Regardless of the details of

2 operation chosen however, the invention disclosed in Figure

3 11 provides a minimum of 3 spaced electrodes means that

4 provides measurement information related to current flow into

5 formation, and respectively, first and second compensation

6 information related to measurements of R1 and R2 between

7 respectively electrodes C-D, and D-E that are used to

8 determine a magnitude related to formation resistivity.

9 Altogether, Figure 11 shows a total of 7 each voltage

10 measurement electrodes operated as 4 pairs of voltage

11 measurement electrodes.

12

13   Figure 12 is similar to Figure 11 except that the extra

14 potential voltage measurement electrodes P-Q and

15 R-S have been removed.   It should be noted that the apparatus

16 defined in Figure 12 results in knowledge of the measurement

17 current leaking into formation, knowledge of the resistance

18 R1 between voltage measurement electrodes C-D, and the

19 knowledge of the resistance R2 between voltage measurement

20 electrodes D-E.   Therefore, the apparatus in Figure 12

21 provides knowledge of the net current at F(1) flowing through

22 resistor R1 between electrodes C-D.   Similarly, the apparatus

23 in Figure 12 provides knowledge of the net current at F(1)

24 flowing through resistor R2 between electrodes D-E.   Extra

25 control circuitry, not shown, can be adapted as in Figure 6

26 to minimize the net counter-flowing currents flowing by the

27 combined resistors R1 and R2 to improve measurement accuracy.

28 Regardless of the details of operation chosen however, the

29 invention disclosed in Figure 12 provides a minimum of 3

30 spaced apart electrode means that provide measurement

31 information related to current flow into formation, and

32 respectively, first and second compensation information

33 related to measurements of R1 and R2 between respectively

34

1   electrodes C-D, and D-E that are used to determine a
2   magnitude related to formation resistivity.
3
4   The apparatus in Figure 12 may be operated in a
5   particularly simple manner. Information from pair C-D can be
6   used to control the magnitude of the current flowing along
7   the casing at the frequency of F(1), and keep it constant.
8   Then information from pair D-E can be used to infer
9   geophysical parameters from measurements of the current at
10 the frequency of F(1). Despite the fact that the first pair
11 C-D is used primarily herein "to control current", the
12 apparatus so described nonetheless requires 3 spaced apart
13 voltage measurement electrodes which engage the interior of
14 the casing and is therefore simply another embodiment of the
15 invention herein.
16
17   Figure 13 is functionally identical to Figure 26 from
18 Serial No. 07/089,697 that is U.S. Patent No. 4,882,542,
19 showing an apparatus having multiple voltage measurement
20 electrodes engaging the interior of the casing that is marked
21 with the legend "Prior Art". Individual potential voltage
22 measurement electrodes k, l, m, n, o, p, q, r, s, and t
23 electrically engage the casing. In principle, any total
24 number Z of such potential voltage measuring electrodes can
25 be made to electrically engage the interior of the casing.
26 During the calibration step described in Vail(542), current
27 is passed along the casing resulting in the knowledge of the
28 respective casing resistances between each potential voltage
29 measurement electrode. The casing resistance between
30 electrodes k and l is defined herein as R(k,l). The casing
31 resistance between electrodes l and m is defined herein as
32 R(l,m). The casing resistance between m and n is defined
33 herein R(m,n). The casing resistance between n and o is
34 defined herein as R(n,o). By analogy, the casing resistances

R(o,p), R(p,q), R(q,r), R(r,s) and R(s,t) are defined herein.
In principle, any number of casing resistances can be defined
for any number Z of electrodes which electrically engage the
interior of the casing. The distance along the casing
between electrodes k and l is defined herein as L(k,l). The
distance along the casing between electrodes l and m is
defined herein as L(l,m). The distance along the casing
between electrodes m and n is defined herein as L(m,n). The
distance along the casing between electrodes n and o is
defined herein as L(n,o). By analogy, the distances of
separation of appropriate electrodes are defined herein as
L(o,p), L(p,q), L(q,r), L(r,s,) and L(s,t). In principle,
any number of distances can be defined between any number Z
electrodes which electrically engage the interior of the
casing. The distance of separation between electrodes can be
chosen to be any distance. They may be chosen to be equal or
they can be chosen not to be equal, depending upon chosen
function. For example, L(k,l) can be chosen to be 3 inches.
L(l,m) can be chosen to be 6 inches. L(m,n) can be chosen to
be 12 inches. L(n,o) can be chosen to be 20 inches. L(o,p)
can be chosen to be 52 inches. L(p,q) can be chosen to be 60
inches. L(q,r) can be chosen to be 120 inches. Further,
electrodes s and t can be disconnected. Such an array can
measure the potential voltage distribution along the casing
or the potential voltage profile along the casing in response
to calibration currents primarily flowing along the casing
and in response to the measurement currents flowing along the
casing and into the formation. The calibration current can
be at chosen to be the same frequency as the measurement
current as originally described in Vail(989) or can be at a
different frequency as described in Vail(626). The above
described variable spacing can be used to infer the vertical
and radial variations of the geological formation, the
vertical distribution of geological beds, and other

geological information. Regardless of the details of
operation chosen however, the invention disclosed in Figure
13 provides a minimum of 3 spaced apart voltage measurement
electrode means that provide measurement information related
to current flow into formation, and respectively, first and
second compensation information related to measurements of at
least two casing resistances respectively between the three
voltage measurement electrodes, wherein said measurement
information and the first and second compensation information
are used to determine a magnitude related to formation
resistivity. Figure 12 and the text herein further shows
that a plurality of spaced apart electrodes along the casing,
which may be chosen to be spaced at various different
intervals, provide multiple measurements of quantities
related to current flow into formation, and provide multiple
measurements of the resistances of the casing spanned by the
particular number of chosen spaced apart electrodes that may
be used to infer geophysical information including the
resistivity of the adjacent formation.

It should also be noted that Serial No. 07/089,697
{Vail(542)} describes many different means to measure voltage
profiles on the casing including those shown in Figures 25,
26, 27, 28, and 29 therein. Those drawings describe several
other apparatus geometries having multiple electrodes.

It may also be worthwhile to note here that several of
the figures show different preferred embodiments of the
invention. In Figures 1, 2, 3, 4, and 5, switch 22 is in
one of several positions, so this switch "alters" between one
state and another one, and hence such methods of measurement
are sometimes referred to as an "alter method of
measurement". Figures 6, 7 and 8 explicitly shows two
frequencies of operation at the same time, and hence, such

methods of measurement are sometimes referred to as a "two frequency method of measurement". In Figures 6, 7, and 8, F(2) may be any frequency, and F(1) may be any frequency - provided the other above requirements for the measurement are otherwise satisfied. It is also evident from the above description that more than two frequencies may be used, and hence such methods of measurement are sometimes referred to as a "multiple frequency of method of measurement". And lastly, it is possible to perform measurements of resistivity using hybrid methods, wherein certain measurements are performed at one stage of an "alter method of measurement", and yet other measurements are performed using a "two frequency method of measurement" and/or a "multiple frequency method of measurement". There are many variations of the preferred embodiments of the invention.

Therefore, measurements of the current leakage may be performed using an "alter method of measurement", a "two frequency method of measurement" or a "multiple frequency method of measurement".

Therefore, measurements of the potential voltage may be performed using an "alter method of measurement", a "two frequency method of measurement" or a "multiple frequency method of measurement".

Various embodiments of the invention herein provide many different manners to introduce current onto the casing, a portion of which is subsequently conducted through formation. Various embodiments herein provide many different methods to measure voltage levels at a plurality of many points on the casing to provide a potential voltage profile along the casing which may be interpreted to measure the current leaking off the exterior of the casing from within a finite

vertical section of the casing. Regardless of the details of
operation chosen however, the invention herein disclosed
provides a minimum of 3 spaced apart voltage measurement
electrode means that provides measurement information related
to current flow into the geological formation, and
respectively, first and second compensation information
related to measurements of at least two separate casing
resistances between the three spaced apart voltage
measurement electrodes, wherein the measurement information
and the first and second compensation information are used to
determine a magnitude related to formation resistivity.

Figure 14 is an exact copy of Figure 24 from U.S.
Patent No. 4,882,542 {Vail(542)}, that issued on 11/21/1989,
that is Serial No. 07/089,697, that has the filing date
of 8/26/1987. Here, the number of the figure has been
changed from "Fig. 24" to "Fig. 14". All the numerals
through numeral 42 have already been defined herein.
The following excerpt is quoted from Serial No. 07/089,697
{Vail(542)} commencing on page 20, line 3, and ending on
page 20, line 61, as follows (except that the phrase
"Fig. 24" has been replaced by the phrase "Fig. 14"):

"Fig. 14 shows another embodiment of the invention. The
purpose of Fig. 14 is to present various alternatives
for the placement of electrode B and to further discuss
requirements which electrode B must satisfy for proper
operation of various embodiments of the invention.
Here, most all of the elements have been defined in
Fig. 1 except here SW1C replaces SW1 in Fig. 1.
Switch SW1C may be used to connect to alternative
grounding positions shown figuratively as B, B_1, B_2, and
B_3 in Fig. 14. Electrode B has already been described.
B_1 is an electrode in electrical contact with the

interior of the casing which is located beyond a
critical distance, L_c, away from electrode A.

As long as the length of casing between A and B_1, L_8, is
comparable to or larger than L_c, then the electric field
is primarily perpendicular to the casing when electrode
A is energized, and the invention works in the usual
fashion. The critical distance L_c is that length of
casing adjacent to a formation where the series
resistance to current flow equals the contact resistance
of the pipe adjacent to the formation. (For a uniform
formation, that distance can be calculated by requiring
that at a particular length L_c, the series resistance to
current flow along the length L_c of the casing which is
given by the algebraic expression (L_c r), where r is
defined in Eq. 1, is equal to the resistance R_c in Eq. 6
for the particular length L_c / 2. This equation is then
solved for the length L_c. This is also the approximate
distance where half of the current flows off the casing
into the formation which has already been discussed).
The requirement on the length of L_8 is a matter of
convenience only, because for shorter lengths of L_8, as
long as the placement of electrode B_1 is such that it
allows the generation of any significant component of
the electric field perpendicular to the casing in the
vicinity of electrode A, then current is conducted into
formation from the casing adjacent to electrode A, and
the invention functions properly. In addition, B_2 is an
electrode in electrical contact with the top of the
borehole casing. Here too, as long as the resistance of
the length of casing between A and B_2 is comparable to
or larger than the total resistance to current flow
between electrode A and electrode B, then the electric
field is primarily perpendicular to the casing when
electrode A is energized, and the invention works in the

1   usual fashion. And finally, B_3 is another earth ground,
2   and it's position is immaterial provided that the
3   electric field produced on the exterior of the casing is
4   primarily perpendicular to the casing which will allow
5   proper measurement of the resistivity of the geological
6   formation. Although the electric field is primarily
7   perpendicular to the casing at great depths independent
8   of the position of the ground return (B, B_1, B_2, or B_3),
9   there none-the-less should be small detectable
10   differences related to the different current paths.
11   Therefore, different grounding returns could provide a
12   means of measuring the resistivity of different selected
13   portions of the formation such as the resistivity of
14   different quadrants. Such measurements are only a minor
15   modification of the invention."
16
17   As stated earlier, all the elements through element 42
18   in Figure 14 have already been defined. The remaining
19   legends in Figure 14 are listed as follows: L_7, that is the
20   distance below the surface to the earth to electrode B_1;
21   L_8, that is the distance between electrode B_1 and
22   electrode A; r_1, that is the radial distance from the cased
23   well to electrode B; and r_3 that is the radial position from
24   the well to electrode B_3.
25
26   It should be noted that above described calculation for
27   L_c is explicitly presented in Equation 1 on page 9 of U.S.
28   Patent No. 5,187,440 {Vail(440)} that issued on 2/16/1993,
29   that is Serial No. 07/749,136, and that has the Filing Date
30   of 8/23/91, an entire copy of which is included herein by
31   reference.
32
33   It is useful to further discuss certain the above quote
34   related to Figure 14. One sentence reads: "The requirement

1 on the length of L_8 is a matter of convenience only, because
2 for shorter lengths of L_8, as long as the placement of
3 electrode B_1 is such that it allows the generation of any
4 significant component of the electric field perpendicular to
5 the casing in the vicinity of electrode A, then current is
6 conducted into formation from the casing adjacent to
7 electrode A, and the invention functions properly." The
8 critical operational term here is "...generation of any
9 significant component of the electric field...".

11 Another sentence in that long quote related to Figure 14
12 reads as follows: "Although the electric field is primarily
13 perpendicular to the casing at great depths independent of
14 the position of the ground return (B, B_1, B_2, or B_3), there
15 none-the-less should be small detectable differences related
16 to the different current paths. Therefore, different
17 grounding returns could provide a means of measuring the
18 resistivity of different selected portions of the formation
19 such as the resistivity of different quadrants. Such
20 measurements are only a minor modification of the invention."

22 One "...minor modification of the invention..." quoted
23 above, relates to the above observation that many different
24 positions electrode B_1 result in the "...the generation of
25 any significant component of the electric field perpendicular
26 to the casing in the vicinity of electrode A...". Further,
27 the "...different grounding returns could provide a means of
28 measuring the resistivity of different selected portions of
29 the formation..." From this description, it is evident that
30 another preferred embodiment of the invention provides a
31 means of adjusting the magnitude of the electric field
32 perpendicular to the casing applied to any one geological
33 formation at chosen depth z in Fig. 14 by performing
34 measurements with electrode B_1 placed at a first distance

L$_8$(a) above electrode A; and then by performing measurements
with electrode B$_1$ placed a second distance L$_8$(b) above
electrode A; and then by performing measurements perhaps
another time by performing measurements at a third distance
L$_8$(c) above electrode A. In principle, any number of such
measurements could be made.

Furthermore, there is no particular necessary reason in
a deep well, with sufficient casing below electrode F, that
electrode B$_1$ must be located above electrode A. In fact,
with a sufficiently deep well, electrode B$_1$ may be located at
any chosen distance below electrode F. In this preferred
embodiment, electrode B$_1$(L$_8$) may be placed at any distance L$_8$
above electrode A. Here, the position of electrode B$_1$ is a
function of L$_8$. Similarly, any such electrode that is
located below electrode F would be separated by a distance L$_9$
below electrode F. This electrode will be defined herein to
be B$^*_1$(L$_9$), where the quantity B$^*_1$ indicates that electrode
is located below electrode F in Figure 14, and is at a
distance L$_9$ below electrode F in Figure 14. However, these
legends have not been added to Figure 14 for the sake of
simplicity. Further, the current return electrode B$_1$ above
electrode A, and any current return electrode B$^*_1$ located
below electrode F in Figure 14 may be energized
simultaneously using apparatus and methods already described
above. This in turn provides "...means of measuring the
resistivity of different selected portions of the
formation...". In particular, if the strength of the
electric field perpendicular to the casing is adjusted from a
first value of the electric field to a second value of the
electric field, wherein said second value is greater than the
first value, then it is evident that the "radius of
investigation" of the formation has been increased. In
general, for any particular value of the electric field

1   perpendicular to the casing, there is an appropriate "radius

2   of investigation" for that magnitude of electric field.

3   Performing measurements for various different positions of

4   one, or more current return electrodes, provides a method for

5   measuring the resistivity of the geological formation for

6   different radii of investigation. Therefore, adjusting the

7   various different current return electrodes in the casing

8   provides methods of operation to vary the "radius of

9   investigation", a term defined herein.

10

11   The preferred embodiments described above in relation to

12   Figure 14 provides a means of adjusting the magnitude of the

13   electric field perpendicular to the casing applied to any one

14   geological formation at any depth z in Fig. 14 by performing

15   measurements with different placements of one or more of the

16   current return electrodes. For any such magnitude of applied

17   electric field, then plots similar to those shown in Figure 2

18   will be obtained. However, for larger applied fields, the

19   maximum value of ΔI will be correspondingly larger. Put

20   another way, for a first value of the applied electric field,

21   then a first value of ΔI(first) will be observed. For a

22   larger second value of the applied electric field, then a

23   second value of ΔI(second) will be observed. In the example

24   cited, ΔI(second) will be larger than ΔI(first).

25   Such procedures amount to adjusting the radius of

26   investigation, or the "50% radius of investigation",

27   a term used in the above defined literature.

28

29   In Vail(440), Figure 6 therein shows yet another

30   grounding position, or one more position for another current

31   return electrode that is labeled with the legend B_4 therein.

32   The point is that the inventor has provided many possible

33   positions for one or more current return electrodes

34   generically identified by the symbol "B" in many of the

figures related to the Vail Patents in this field. For
many preferred embodiments, the term "grounding position",
"current return electrode", "ground return electrode",
"ground return electrode in the cased well", "current return
electrode to generate an electric field in the formation
exterior to the casing", and similar variations, may all be
used equivalently for the purposes herein.

In addition, Figure 48 in U.S. Patent No. 4,882,542
Vail (542) shows at least two apparatus disposed within a
drill pipe, each having their own current introducing
electrodes.

Yet further, Figures 6-12 herein each have multiple
sets of current introducing electrodes disposed within the
wellbore.

Therefore, the invention has described many different
preferred embodiments of apparatus and methods of operation
that provide for two or more current conducting electrodes in
electrical contact with the interior of the casing to measure
formation resistivity. The invention has further described
many different preferred embodiments of the apparatus and
methods of operation that provide for at least two current
conducting electrodes in electrical contact with the interior
of the casing and one in contact with the top of the casing
to measure formation resistivity.

Accordingly, the invention has provide apparatus and
methods of operation to determine the resistivity of a
formation adjacent to a borehole having casing with an
apparatus having all the current conducting electrodes
within the cased well. Figure 14 shows such an apparatus
when element 22 is connected through SW1C to electrode B_1.

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1   Therefore, and with reference to Figure 14 and other
2 related figures herein, one embodiment of the invention is an
3 apparatus to provide information useful to determine the
4 resistivity of a geological formation from within a cased
5 well that has a first electrode that electrically engages a
6 first particular section of casing at a specific depth within
7 the well for receiving first signals having voltage related
8 information; a second electrode that electrically engages the
9 first particular section of casing for receiving second
10 signals having voltage related information located a first
11 distance above said first electrode wherein the magnitude of
12 the resistance of the portion of casing between said first
13 and second electrodes is the first resistance; and a third
14 electrode that electrically engages the first particular
15 section of casing for receiving third signals having voltage
16 related information located a second distance below said
17 first electrode wherein the magnitude of the resistance of
18 the portion of casing between said first and third electrodes
19 is the second resistance. This embodiment also has a fourth
20 electrode that electrically engages the casing at a point
21 located a third distance above said second electrode and
22 a fifth electrode that electrically engages the casing at a
23 point located a fourth distance above said fourth electrode.
24 This embodiment also provides means to conduct a first
25 current from said fourth electrode to said fifth electrode.
26 Further, said fourth distance is chosen such that at least a
27 portion of said first current flows into the formation of
28 interest. Figure 14 shows an apparatus having means to
29 measure said first resistance and said second resistance.
30 Figure 14 also shows means for processing said first, second
31 and third signals from said first, second, and third
32 electrode means thereby providing information useful to
33 determine the resistivity of the formation of interest.
34

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With reference to Figure 14 and to other related figures and disclosure, another embodiment provides information useful to determine the resistivity of a geological formation from within a cased well by providing an apparatus having a first electrode that electrically engages a first particular section of casing for receiving first voltage related signals at a specific depth within the well; having a second electrode that electrically engages the first particular section of casing for receiving second voltage related signals located a first distance above said first electrode wherein the magnitude of the resistance of the portion of casing between said first and second electrodes is the first resistance; and a third electrode that electrically engages the first particular section of casing for receiving third voltage related signals located a second distance below said first electrode wherein the magnitude of the resistance of the portion of casing between said first and third electrodes is the second resistance. The apparatus also has a fourth electrode that electrically engages the casing at a point located a third distance above said second electrode and a a fifth electrode that electrically engages the casing at a point located a fourth distance above said fourth electrode. The apparatus has means to conduct a first current between said fourth and fifth electrodes, and the fourth distance is chosen such that at least a portion of said first current flows into the formation of interest. The apparatus has means to measure said first resistance and said second resistance. Methods are set forth that include obtaining said first, second, and third voltage related signals while conducting said first current between said fourth and fifth electrodes; determining the magnitudes of said first resistance and said second resistance; and processing the voltage related signals from each of said first, second, and

1   third electrodes to provide information useful to determine
2   the resistivity of the geological formation of interest.
3
4   With reference to Figure 14 and related figures, and
5   with further reference to the above disclosure, another
6   embodiment has described a method for providing information
7   useful to determine the resistivity of a geological formation
8   surrounded by borehole casing comprising the steps of causing
9   a first current to flow in a first direction along a
10 predetermined portion of the casing and measuring a plurality
11 of first voltages across said portion of the casing; causing
12 a second current to flow in a first direction along said
13 portion of the casing and measuring a plurality of second
14 voltages across said portion of the casing; and using the
15 first and second voltage measurements to provide information
16 useful to determine the resistivity of a said geological
17 formation. With reference to Figure 14, the term "measuring
18 a plurality of first voltages" means measuring the voltages
19 from electrodes C, D. and E with SW1C connected to electrode
20 B1, and the term "measuring a plurality of second voltages"
21 means measuring the voltages from electrodes C, D, and E with
22 SW1C connected to electrode F. Here, the "first direction"
23 is either up, or down, which may be selected by the settings
24 on the signal generator and the power amplifier.
25
26   With further reference to Figure 14 and other related
27 figures, and with further reference to the above disclosure,
28 another embodiment of the invention describes an apparatus
29 for providing information useful to determine the resistivity
30 of a geological formation surrounded by borehole casing that
31 has a first means to generate and cause a first current to
32 flow in a first direction along a predetermined portion of
33 the casing, a second means to measure a plurality of first
34 voltages across said portion of the casing, a third means to

1   generate and cause a second current to flow in a first
2   direction along said portion of the casing, and a fourth
3   means to measure a plurality of second voltages across said
4   portion of the casing. This apparatus also has processing
5   means using the first and second voltage measurements to
6   provide information useful to determine the resistivity of a
7   said geological formation. With reference to Figure 14, the
8   term "measuring a plurality of first voltages" means
9   measuring the voltages from electrodes C, D. and E with SW1C
10 connected to electrode B1, and the term "measuring a
11 plurality of second voltages" means measuring the voltages
12 from electrodes C, D, and E with SW1C connected to electrode
13 F. Here, the "first direction" is either up, or down, which
14 may be selected by the settings on the signal generator and
15 the power amplifier.
16

17   Many references have been defined herein. In many
18 instances, those references have been actually included in
19 the specification by using the phrase "..., an entire copy of
20 which is included herein by reference." Similar variations
21 of this phrase have been used elsewhere in the specification.
22 To be precise, the phrase "included herein by reference" is
23 also equivalent to the phrase "incorporated herein by
24 reference".
25

26   While the above description contains many specificities,
27 these should not be construed as limitations on the scope of
28 the invention, but rather as exemplification of preferred
29 embodiments thereto. As has been briefly described, there
30 are many possible variations. Accordingly, the scope of the
31 invention should be determined not only by the embodiments
32 illustrated, but by the appended claims and their legal
33 equivalents.
34